QGP Physics − From SPS to LHC

9. J/ψ and Quarkonia as probes of deconfinement

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9.1 Quarkonia

- Quarkonia are heavy quark antiquark bound states, i.e. ccbar and bbar
- since masses of charm and beauty quarks are high as compared to QCD scale parameter Λ_{QCD} ~ 200 MeV
  non-relativistic Schrödinger equation can be used to find bound states

$$(-\frac{\nabla^2}{2(m_Q/2)} + V(r))\Psi(\vec{r}) = E\Psi(\vec{r})$$

with quark-quark potential of the form

$$V(r) = \sigma r - \frac{4}{3}\frac{\alpha_s}{r} + \frac{32\pi\alpha_s}{9}\frac{\vec{s}_1 \cdot \vec{s}_2}{m_Q^2}\delta(\vec{r}) + ...$$

confinement

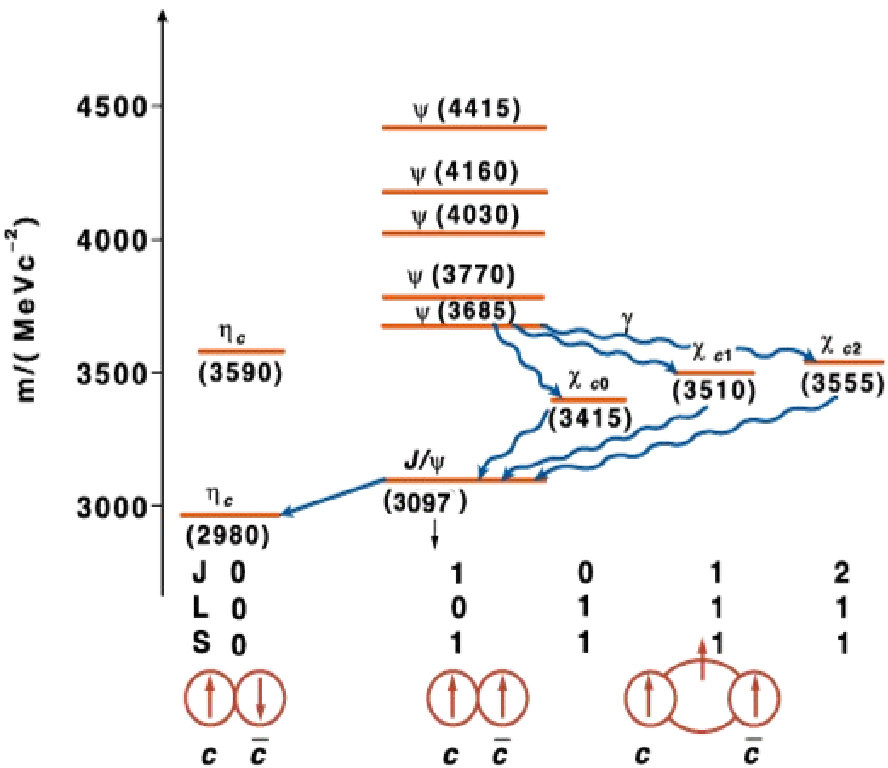
color Coulomb int.

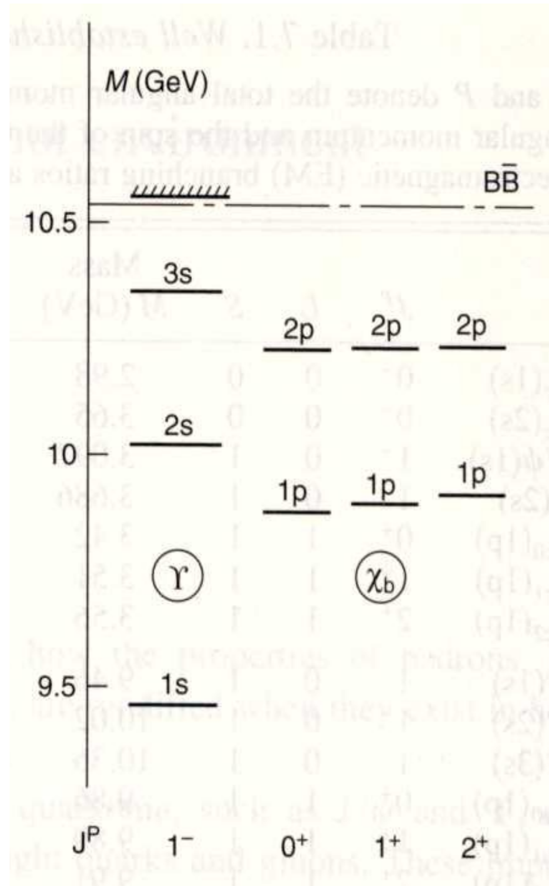
spin-spin int.

tensor, spin-orbit, higher order rel. corr.

- with σ ~ 0.9 GeV/fm, $\alpha_s(m_Q)$ ~ 0.35 and 0.20 for m_c=1.5 and m_b=4.6 GeV
  obtain spectrum of quarkonia

Charmonium and Bottomonium spectra





color singlet states

Charmonium and Bottomonium spectra

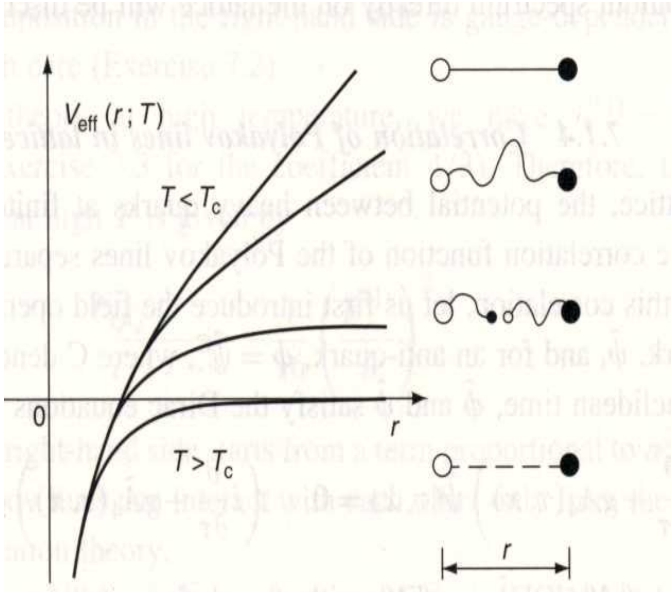
	J^P	L	S	Mass M (GeV)	Total width Γ_{tot} (MeV)	EM branching ratios
$\eta_c(1s)$	0^-	0	0	2.98	~ 16	$B(\gamma\gamma) \sim 0.046\%$
$\eta_c(2s)$	0^-	0	0	3.65	< 55	
$J/\psi(1s)$	1^-	0	1	3.097	~ 0.09	$B(e^+e^-) \sim B(\mu^+\mu^-) \sim 6\%$
$\psi(2s)$	1^-	0	1	3.686	~ 0.28	$B(e^+e^-) \sim B(\mu^+\mu^-) \sim 0.75\%$
$\chi_{c0}(1p)$	0^+	1	1	3.42	~ 11	$B(\gamma\ J/\psi) \sim 1\%$
$\chi_{c1}(1p)$	1^+	1	1	3.51	~ 0.9	$B(\gamma\ J/\psi) \sim 32\%$
$\chi_{c2}(1p)$	2^+	1	1	3.56	~ 2.1	$B(\gamma\ J/\psi) \sim 20\%$
$\Upsilon(1s)$	1^-	0	1	9.46	~ 53	$B(e^+e^-) \sim B(\mu^+\mu^-) \sim 2.4\%$
$\Upsilon(2s)$	1^-	0	1	10.02	~ 43	$B(e^+e^-) \sim B(\mu^+\mu^-) \sim 1.3\%$
$\Upsilon(3s)$	1^-	0	1	10.36	~ 26	$B(\mu^+\mu^-) \sim 1.8\%$
$\chi_{b0}(1p)$	0^+	1	1	9.86		
$\chi_{b1}(1p)$	1^+	1	1	9.89		
$\chi_{b2}(1p)$	2^+	1	1	9.91		

9.2 Charmonia at finite temperature

consider $T \ll m_c$ so QGP of gluons, u,d,s quarks and antiquarks, no thermal heavy quarks
consider ccbar in thermal environment of gluons and light quarks

$$V(r) \rightarrow V_{eff}(r,T) \quad \text{and} \quad m_Q \rightarrow m_Q(T)$$

in QGP color singlet and color octet ccbar states can mix by absorption or emission of a soft gluon
→ modification of V_{eff}



- reduced string tension as T approaches T_c
- string breaking due to thermal qqbar and gluons leading to D and Dbar
- for $T > T_c$ confining part disappears and short range Coulomb part is Debye screened to give Yukawa type potential

$$V_{eff}(r,T) \rightarrow -\frac{4}{3}\frac{\alpha_s}{r}e^{-r/\lambda_D}$$

$$\omega_D = 1/\lambda_D$$

Debye screening mass and length

Debye screening of quarkonia

unlike Coulomb potential, Yukawa potential does not always have bound states

→ dissociation of quarkonia if ω_D sufficiently large at high T

idea: T. Matsui, H. Satz, Phys. Lett. B 178 (1986) 416

compare Bohr radius of charmonia r_B and Debye screening length λ_D

for r_B smaller than λ_D bound states exist even for σ=0

for r_B larger than λ_D no bound states

equivalently to QED where $r_B(\text{hydrogen}) = 1/(m_e\alpha)$ we have: $r_B = 3/(2m_Q\alpha_s)$
and the Debye screening mass:

$$\omega_D^2 = \frac{4\pi\hbar c}{3}\alpha_s T^2 (N_c + \frac{1}{2}N_f)$$

(see textbooks, e.g. Yagi, Hatsuda, Miake, chapter 4, finite temperature field theory)
bound states then disappear for

$$T \geq 0.15 \times m_Q\sqrt{\alpha_s} \approx 0.16\,\text{GeV for J}/\psi\,\text{and}\,0.46\,\text{for}\,\Upsilon$$

Different quarkonia melt at different temperatures

using $$V(r,T) = \frac{\sigma}{\omega_D(T)}(1 - \exp(-\omega_D(T)r)) - \frac{\alpha}{r}\exp(-\omega_D(T)r)$$

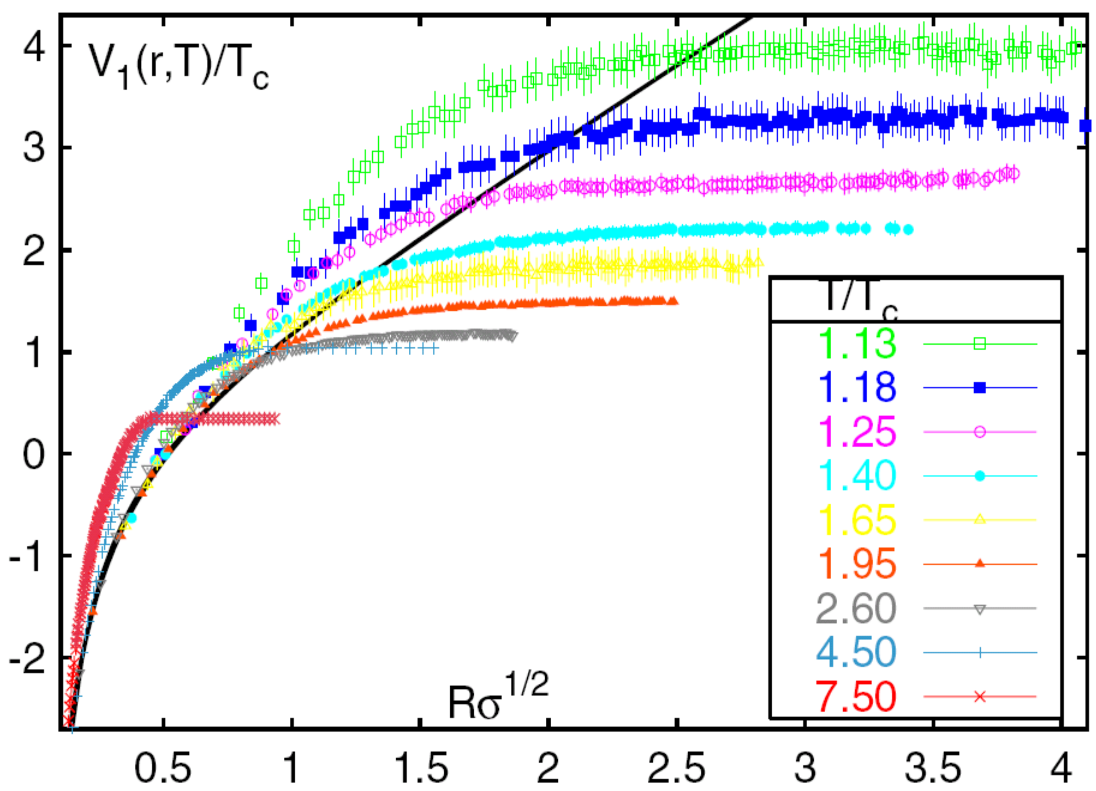
F. Karsch and H. Satz (Z.Physik C51 (1991) 209) obtain:

	J/ψ	ψ'	χ_c	Υ	Υ'
state	1s	2s	1p	1s	2s
mass(GeV)	3.1	3.7	3.5	9.4	10.0
r (fm)	0.45	0.88	0.70	0.23	0.51
T_D/T_c	1.17	1.0	1.0	2.62	1.12
ϵ_D (GeV/fm^3)	1.92	1.12	1.12	43.3	1.65

exact values very model dependent, but basic feature: J/psi, psi', chic, Upsilon' not bound at or little above T_C, Upsilon survives much longer

Results on Debye screening from lattice QCD

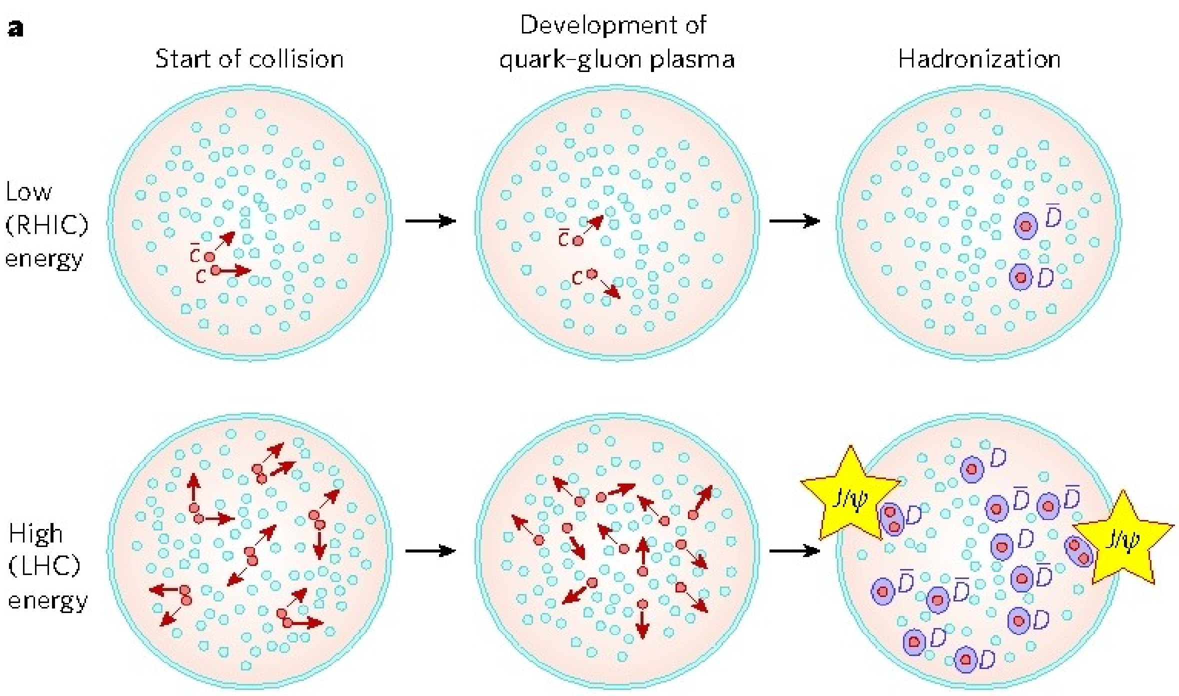
agree qualitatively, quantitatively still a lot of debate, unclear, how to extract effective heavy quark potential
one attempt: correlation of Polyakov lines but there are others



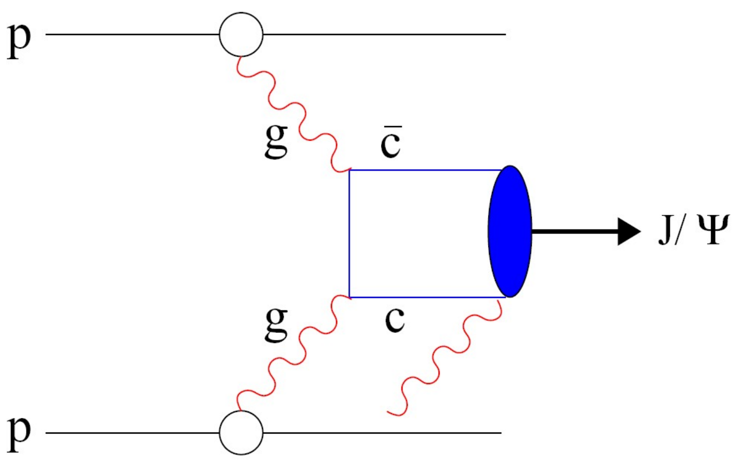
Hadronization of charm quarks

all charm quarks have to appear in charmed hadrons
at hadronization of QGP J/ψ can form again from deconfined quarks
in particular, if number of cc pairs is large (colliders) - $N_{J/\psi} \propto N_{cc}^2$
(P. Braun-Munzinger and J. Stachel,Phys. Lett. B490 (2000) 196)

expect J/psi suppression at low beam energies (SPS, RHIC)
and
J/psi enhancement at high energies (LHC)

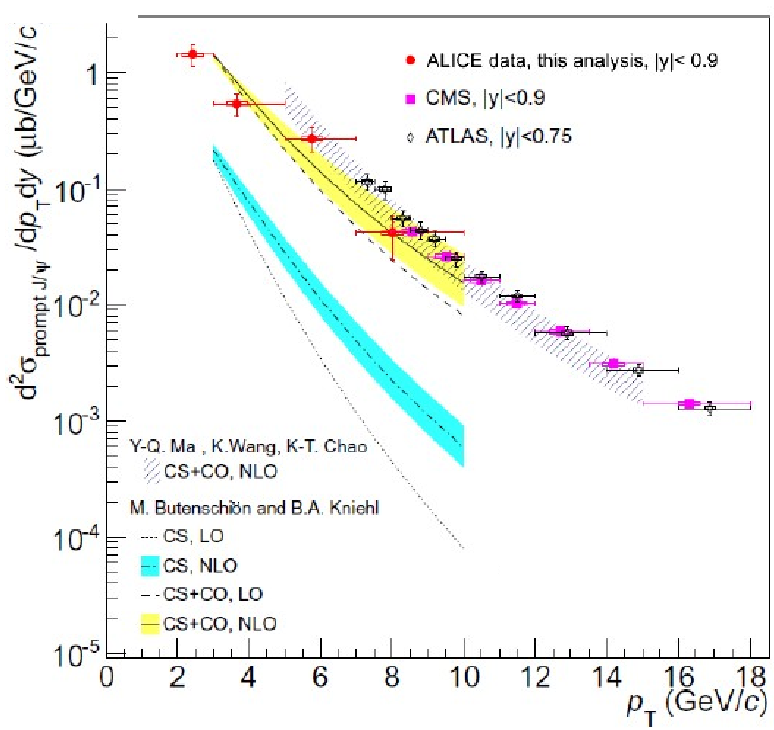


9.3 Production of charmonia in hadronic collisions



- charm and beauty quarks are produced in early hard scattering processes
- most important Feynman diagram: gluon fusion
- formation of quarkonia requires transition to a color singlet state

not pure perturbative QCD anymore, some modelling required
CEM Color Evaporation Model
CSM Color Singlet Model
by now rather successful



relevant time scales

formation of ccbar: in hard initial scattering on time scale $1/2m_c$

with m_c = 1.3 GeV -> τ_{ccbar} = 0.08 fm/c

typical hadron formation time: τ_{hadron} order 1 fm/c

(Blaizot/Ollitrault 1989 Hüfner, Ivanov, Kopeliovich, and Tarasov 2000)

W. Brooks, QM09: description of recent JLAB and HERMES hadron production data in color dipole model - > time scale 5 fm/c

comparable to or longer than QGP formation time:

$\tau_{QGP} \cong$ 1 fm/c at SPS, < 0.5 fm/c at RHIC, $\cong$ 0.1 fm/c at LHC

at LHC even color octet state not formed before QGP (H.Satz 2006)

$$\tau_8 = 1/\sqrt{2m_c\Lambda_{QCD}} \approx 0.25\,\mathrm{fm}$$

collision time: $t_{coll} = 2R/\gamma_{cm}$ at RHIC 0.1 fm/c, at LHC < 5 10^{-3} fm/c

time scales continued

hard	0.05 fm	pre–resonance	0.25 fm	resonance
	$\tau_{c\bar{c}} = 1/2m_c$		$\tau_8 = 1/\sqrt{2m_c \Lambda_{qcd}}$	

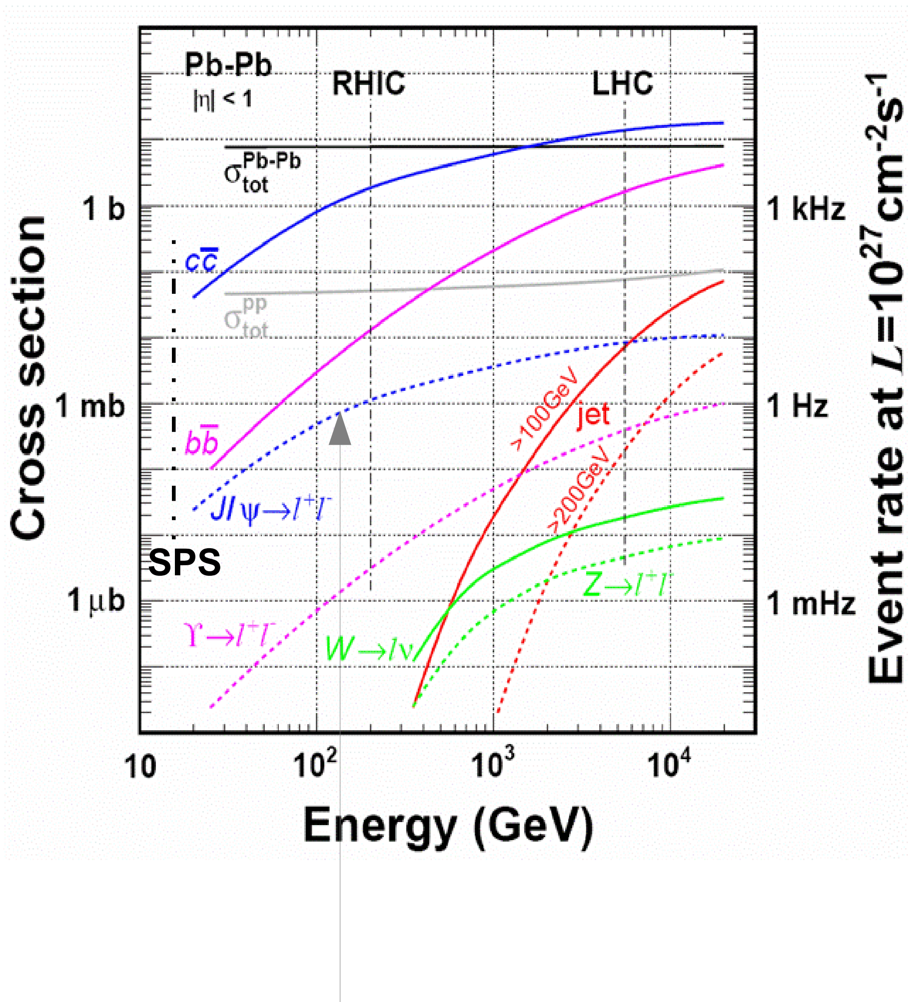
ccbar pairs are formed at collision time scale $t_{coll} = \tau_{ccbar}$

collision time scale comparable to plasma formation time scale and hadron formation time scale at FAIR and SPS $t_{coll} = \tau_{ccbar} \cong \tau_{QGP} \cong \tau_{hadron}$

but at RHIC and much more pronounced at LHC there is the following hierarchy: $t_{coll} = \tau_{ccbar} \ll \tau_{QGP} \ll \tau_{hadron}$

expect that cold nuclear matter absorption effects decrease from SPS to RHIC and are totally irrelevant at LHC

Production of charm and beauty



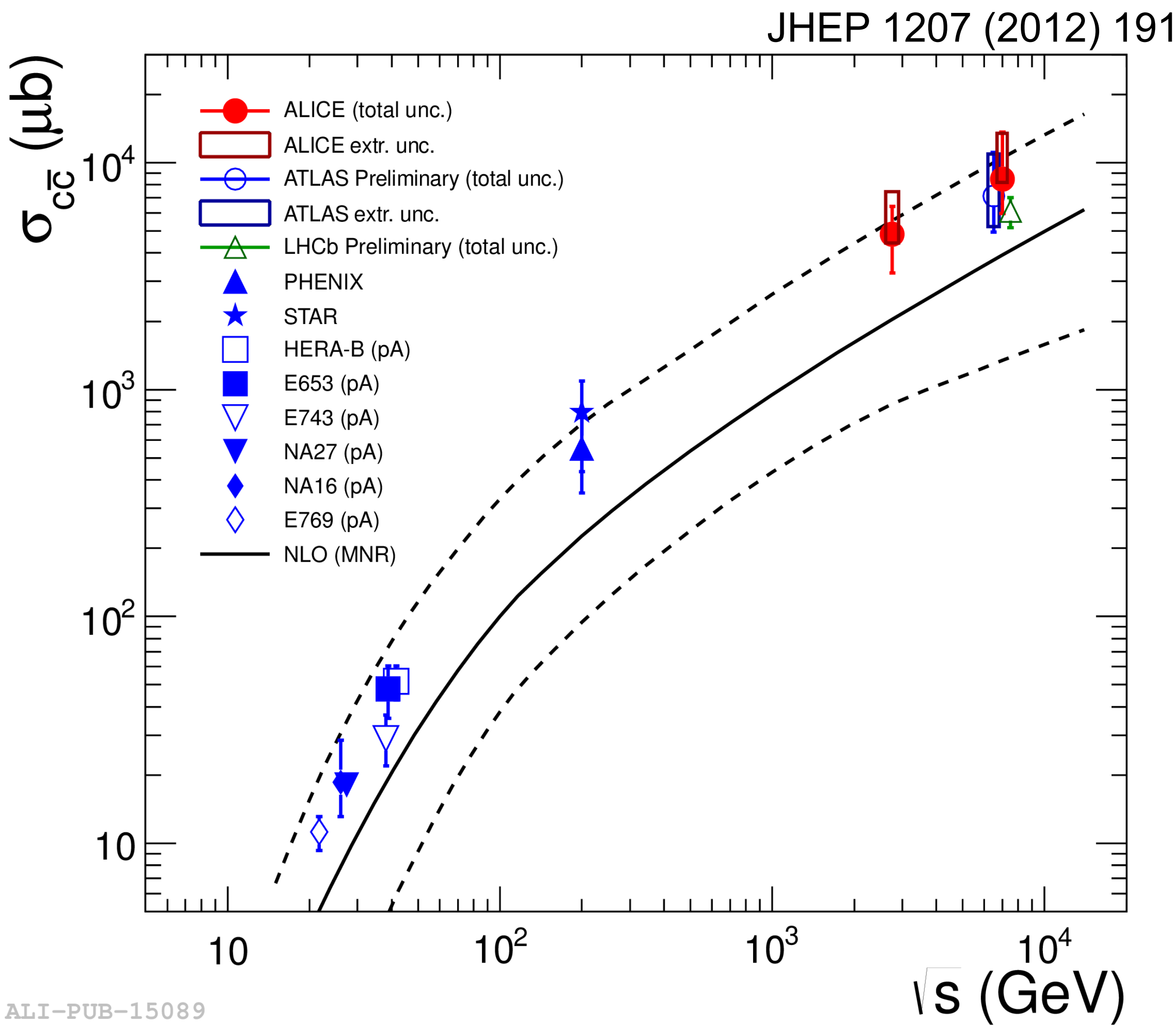
J/ψ is only a small fraction of order of 1% of these 6% detected via l+l- decay

number of heavy quark pairs per central PbPb or AuAu collision from these cross sections:

N($q\bar{q}$) per central AA (b=0)

	SPS	RHIC	LHC
charm	0.2	10	130
bottom	---	0.05	5

a first try at the total ccbar cross section in pp at LHC



- good agreement between ALICE, ATLAS and LHCb
- still large syst. error due to extrapolation to low p_t, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of pQCD but well within uncertainty

9.4 Measurement of quarkonia

$$\mathrm{BR}(\mathrm{J}/\psi \rightarrow \mathrm{hadrons}) \approx 0.88$$

$$\mathrm{BR}(\mathrm{J}/\psi \rightarrow \mathrm{e}^+\mathrm{e}^-) \approx 0.06$$

$$\mathrm{BR}(\mathrm{J}/\psi \rightarrow \mu^+\mu^-) \approx 0.06$$

$$\mathrm{BR}(\psi' \rightarrow \mathrm{hadrons}) \approx 0.98$$

$$\text{of these }\ \mathrm{BR}(\psi' \rightarrow \mathrm{J}/\psi) \approx 0.60$$

$$\mathrm{BR}(\psi' \rightarrow \mu^+\mu^-) \approx 0.008$$

$$\mathrm{BR}(\Upsilon \rightarrow \mathrm{hadrons}) \approx 0.90$$

$$\mathrm{BR}(\Upsilon \rightarrow \mathrm{e}^+\mathrm{e}^-) \approx 0.025$$

$$\mathrm{BR}(\Upsilon \rightarrow)\mu^+\mu^- \approx 0.025$$

J/ψ, ψ' and Υ via e+e- or μ+μ-

χ_c very difficult, usually done via

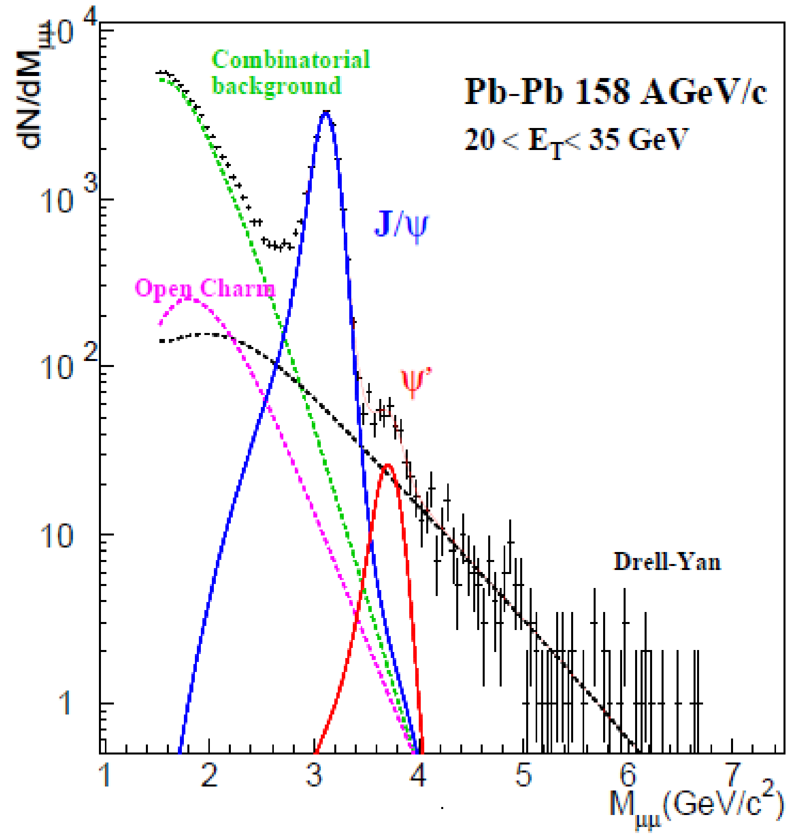
$$\chi_c \rightarrow \mathrm{J}/\psi + \gamma$$

of measured J/ψ typically

$$\approx 60\% \text{ directly produced}$$

$$\approx 10\% \text{ from } \psi' \rightarrow J/\psi$$

$$\approx 30\% \text{ from } \chi_c \rightarrow J/\psi$$



NA50 at CERN SPS

9.5 Charmonia in nuclear collisions

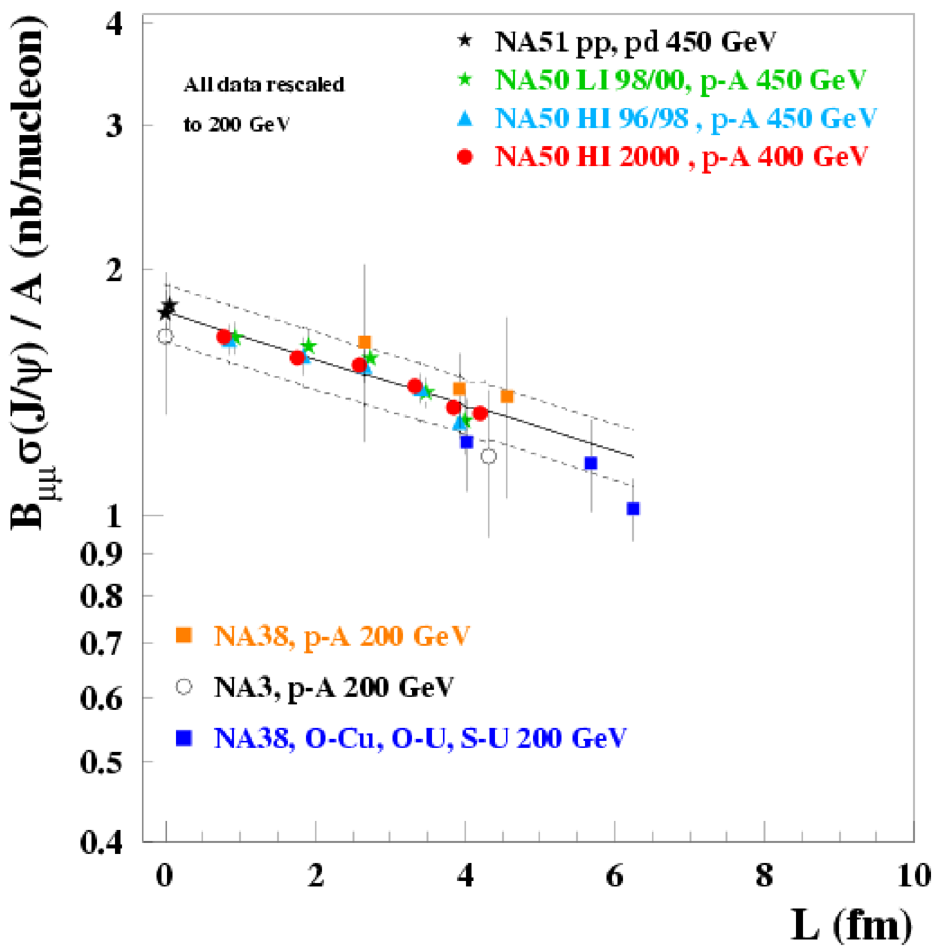
in pA collisions at moderate energies (200-450 GeV) universal picture: prehadronic state absorbed in nuclear matter

$$\sigma(J/\psi) \propto exp(-\rho\sigma_{abs}L)$$

with $\rho = 0.17/\mathrm{fm}^3$
and $\sigma_{\mathrm{abs}} = 4.1 \pm 0.4\mathrm{mb}$

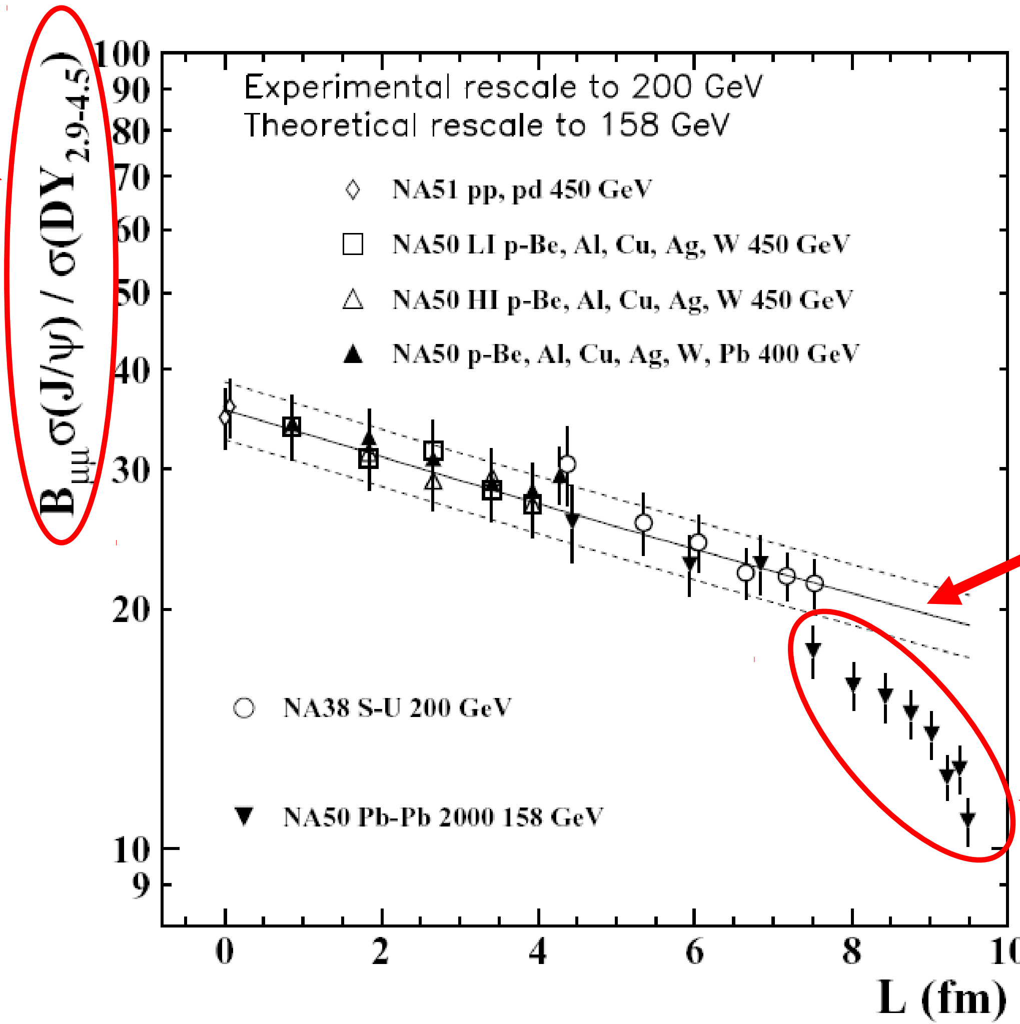
light nuclear collisions follow the same picture

NA50, Eur. Phys. J. C39 (2005) 335



J/psi production in PbPb collisions at SPS energy

normalization to Drell-Yan process



normal J/ψ suppression on nuclear matter

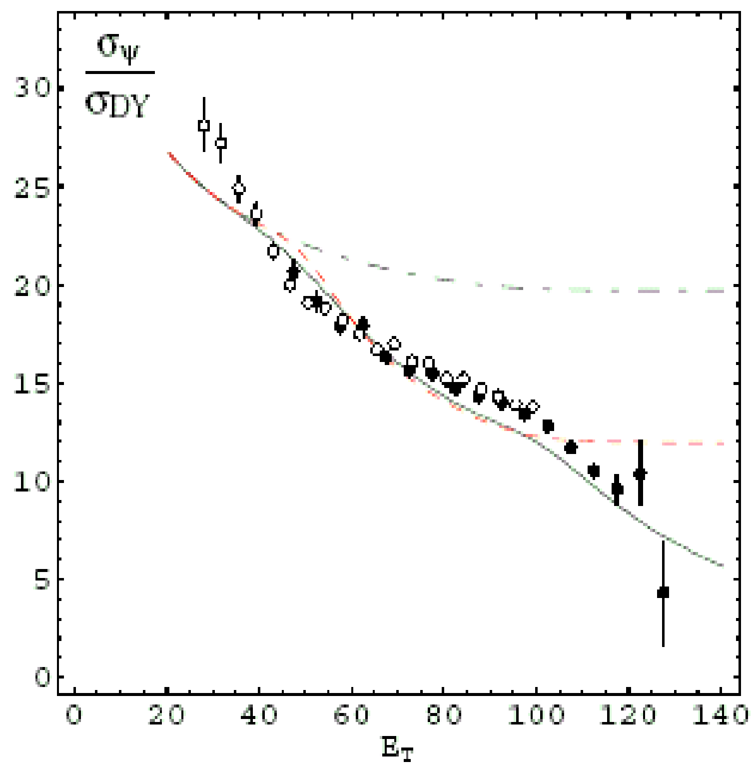
anomalous J/ψ suppression due to QGP?

in central PbPb collisions about 40% less J/ψ than expected from pA systematics

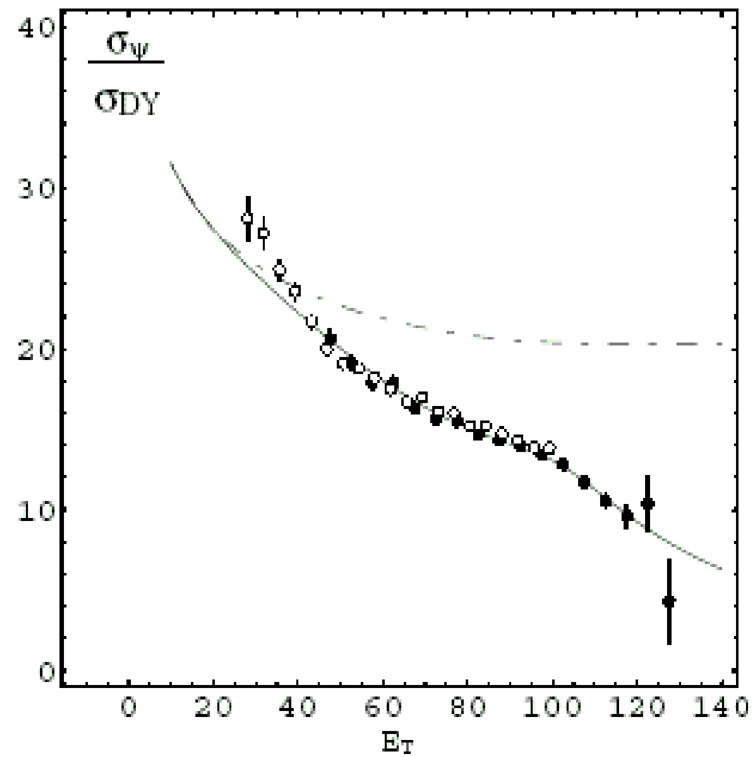
SPS data consistent with suppression at critical density

Dissolution in QGP at critical density n_c (dashes) and in addition with energy density fluctuations (solid)

$n_c = 3.7/\mathrm{fm}^2$



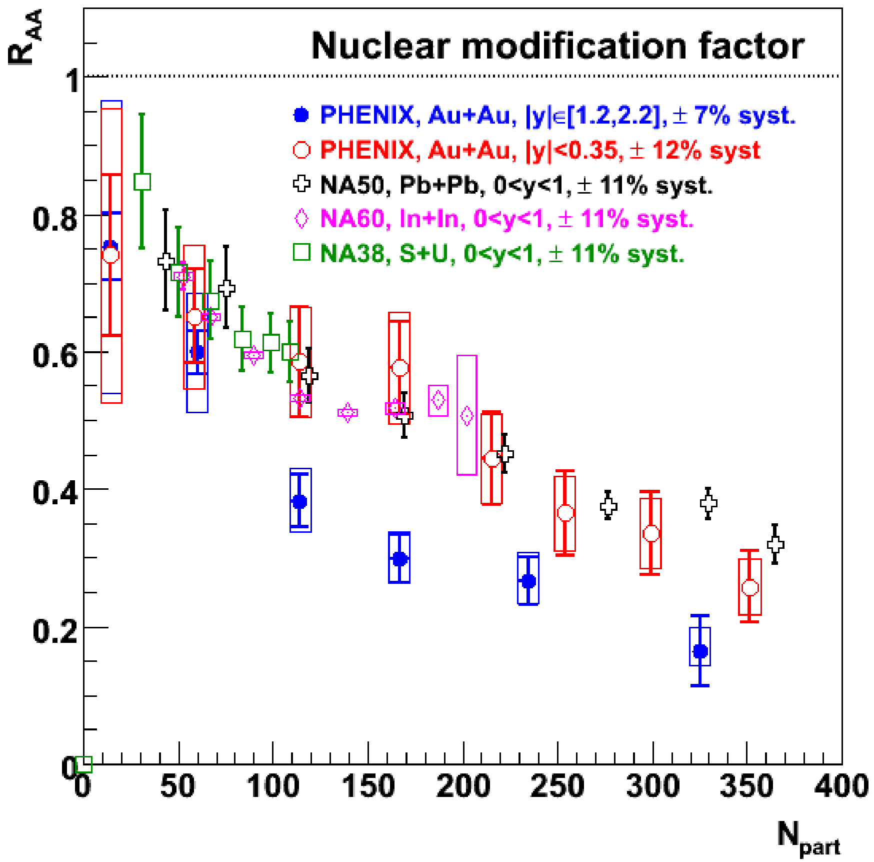
$n_{c1} = 3.3$ and $n_{c2} = 4.2/\mathrm{fm}^2$



J.P. Blaizot, P.M. Dinh, J.Y. Ollitrault, PRL 85 (2000) 4012

J/psi production in AuAu collisions at RHIC

PRL 98 (2007) 232301



at mid-rapidity suppression at RHIC very similar to SPS

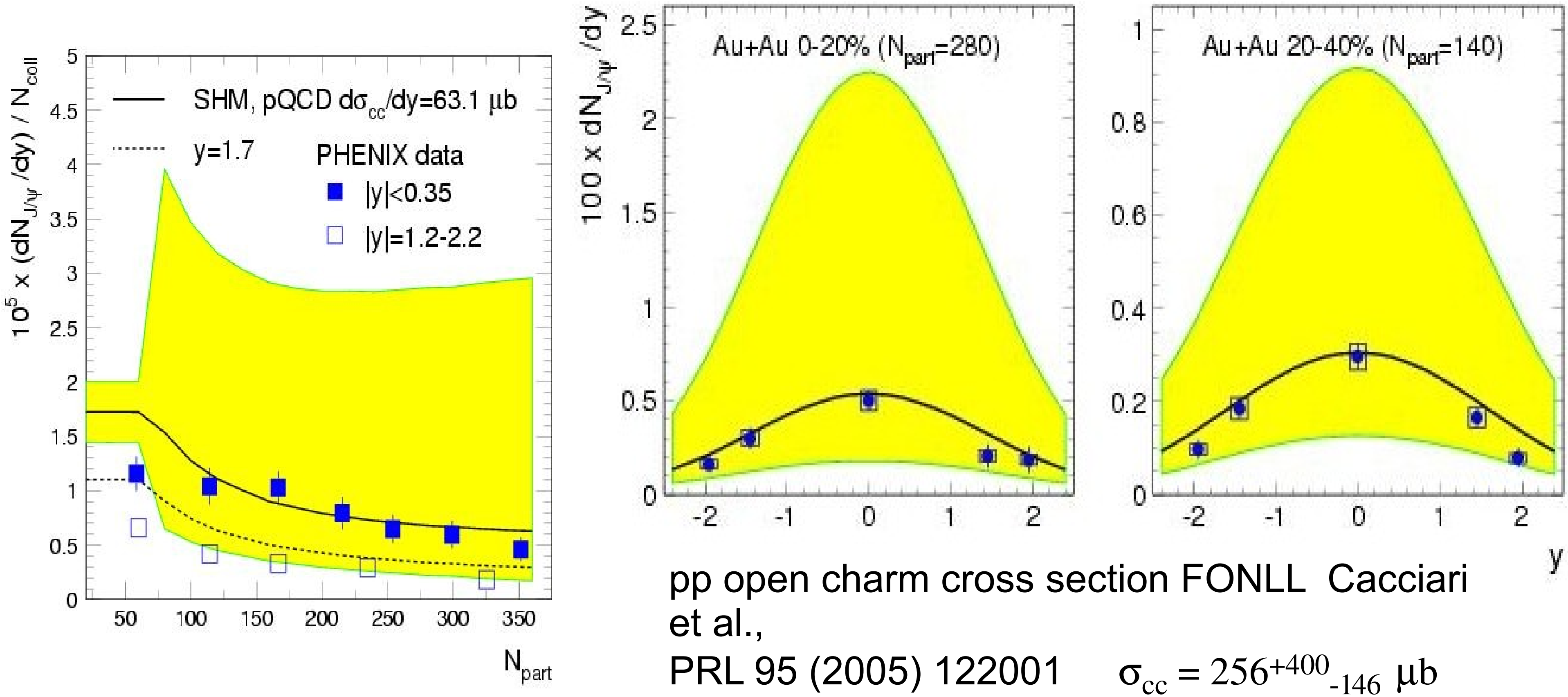
suppression at forward/backward rapidity stronger!

- but prediction (see above): at hadronization of QGP, J/ψ can form from deconfined quarks, in particular if number of ccbar pairs is large

$$N_{J/\psi} \propto N_{cc}^2$$

comparison of statistical model predictions to RHIC data: centrality dependence and rapidity distribution

P. Braun-Munzinger, K. Redlich, J. Stachel, Nucl. Phys. A789 (2007) 334 nucl-th/0611023



pp open charm cross section FONLL Cacciari et al.,
PRL 95 (2005) 122001 $\sigma_{cc} = 256^{+400}_{-146}$ μb

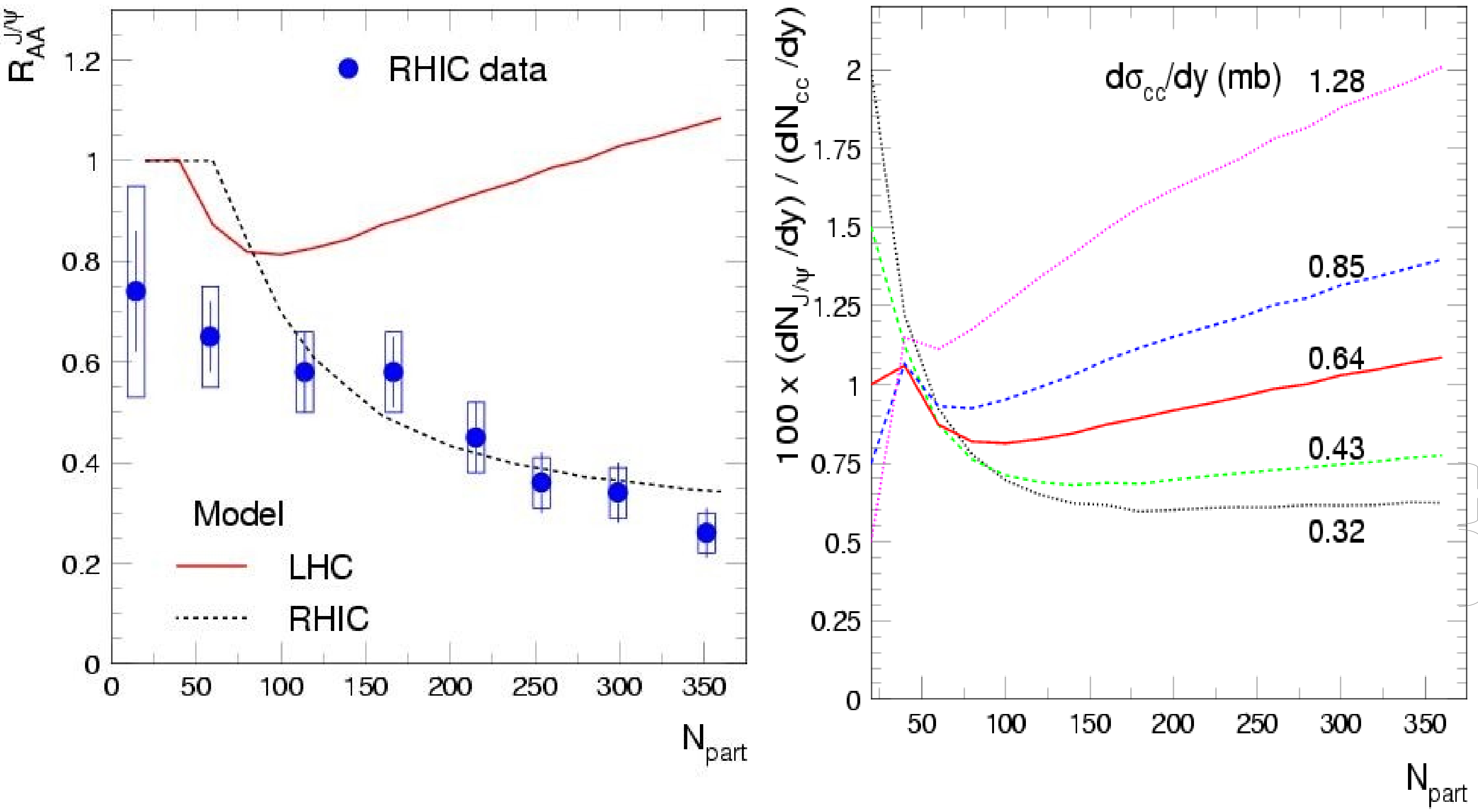
good agreement, no free parameters

↔

but need for good open charm measurement obvious
(this is a lesson for LHC as well!)

energy dependence of quarkonium production in statistical hadronization model

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259

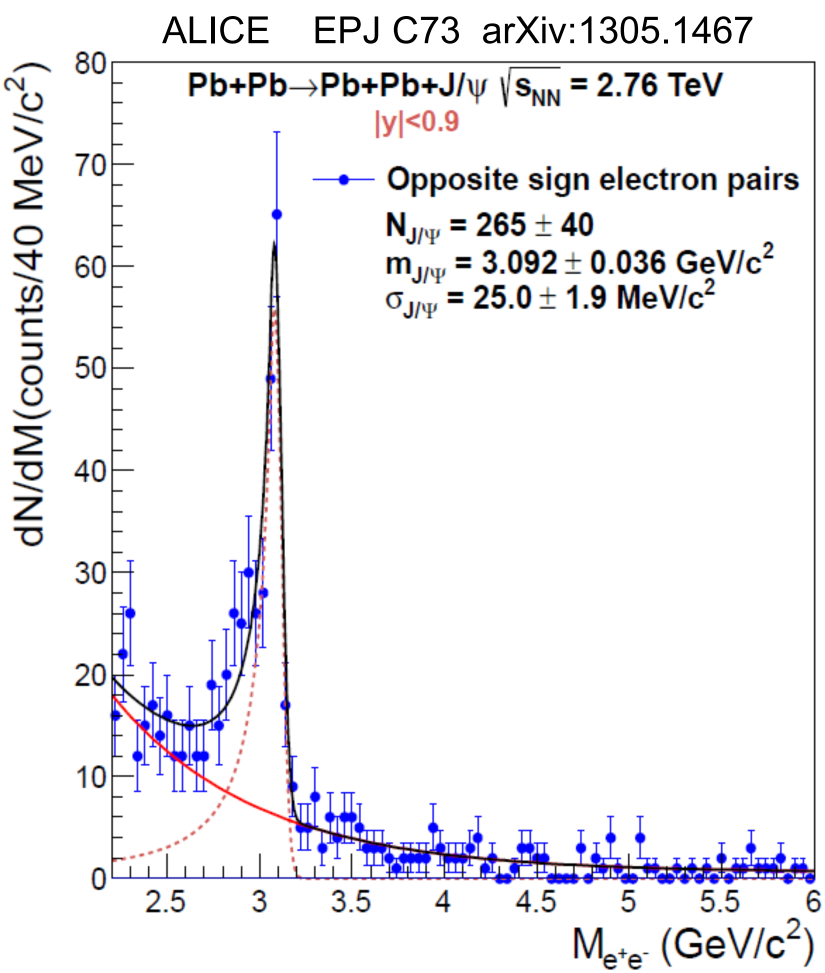


mid-y LHC 2.76 TeV including shadowing

forward-y LHC 2.76 TeV including shadowing

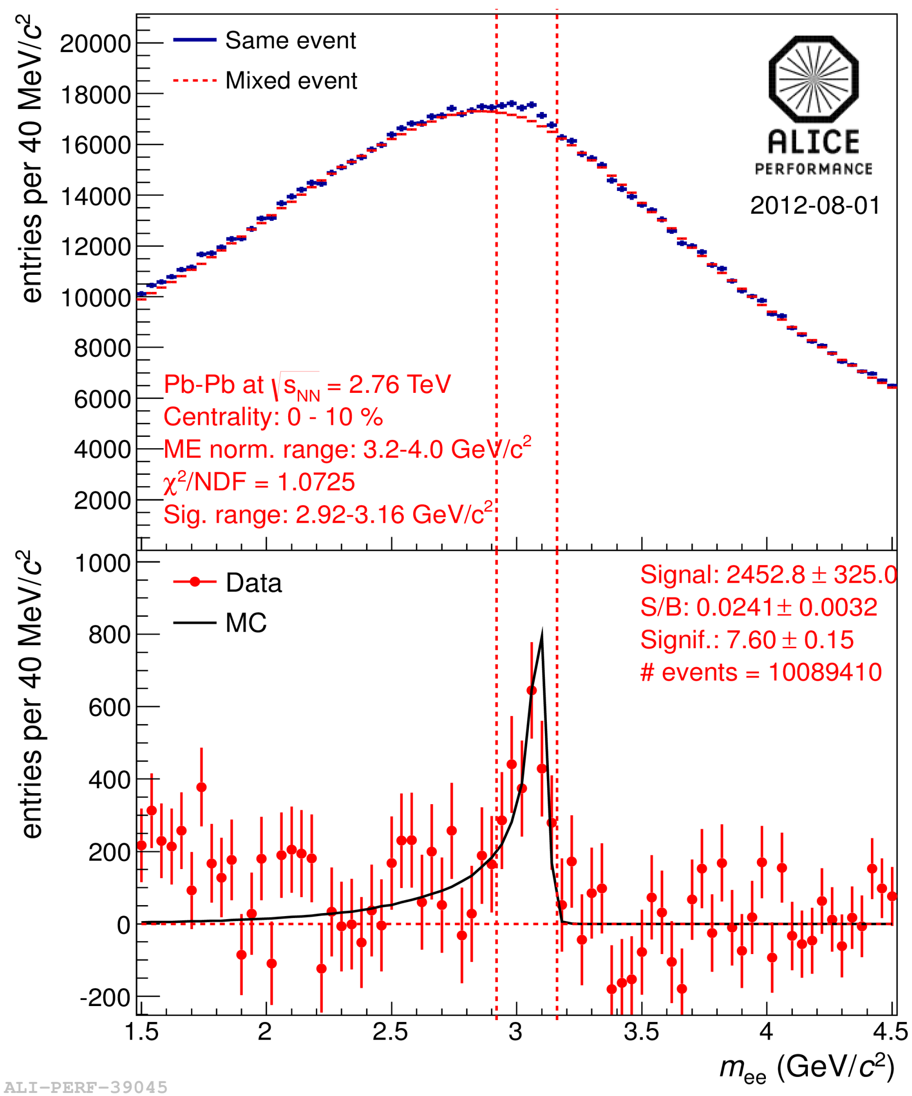
note: stat. model does not make any prediction about ccbar production cross section, this is input; depending on ccbar cross section in nuclear collisions at LHC there can be J/psi enhancement

Reconstruction of J/psi in PbPb collisions at LHC



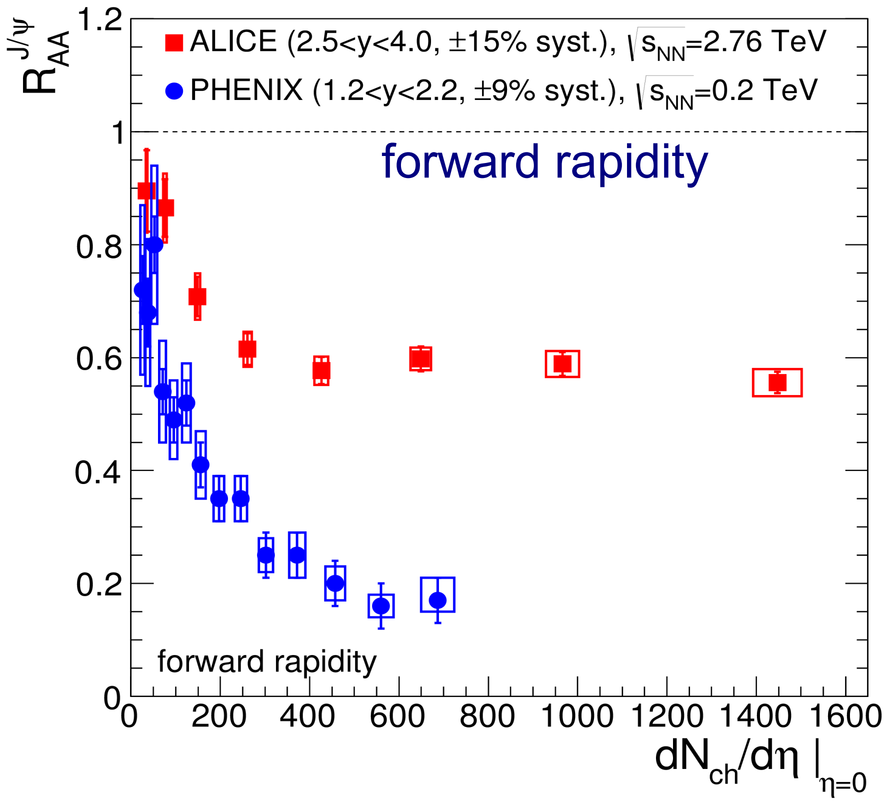
photoproduction in ultra-peripheral PbPb collisions – excellent signal to background very good understanding of line shape

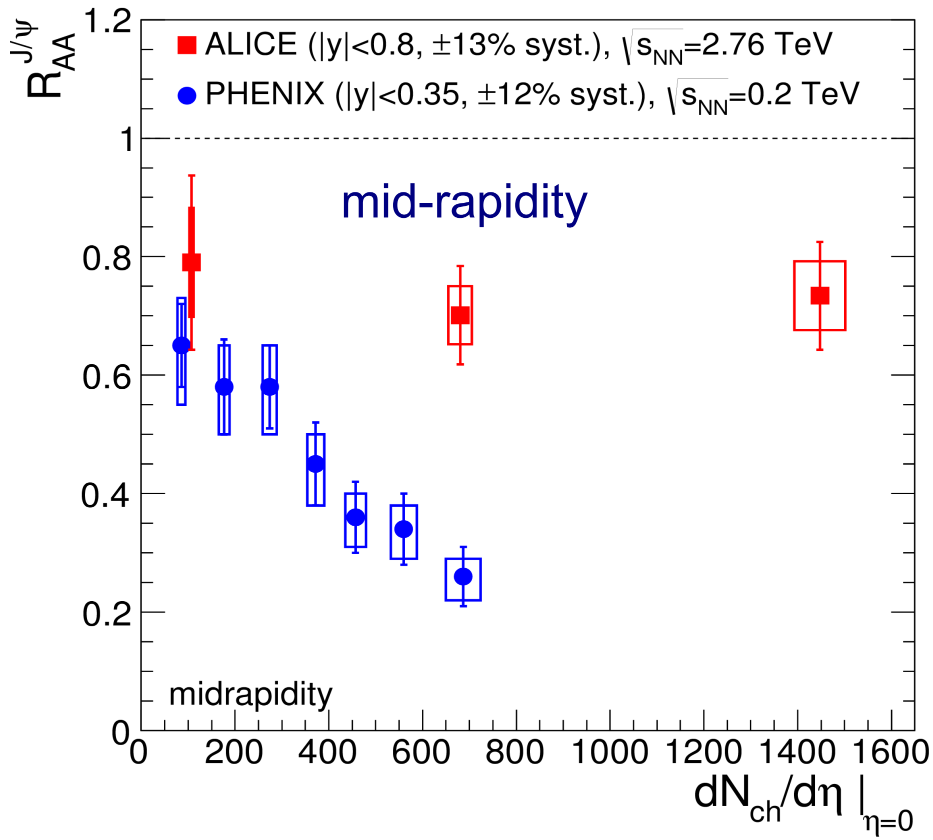
<u>most challenging:</u> central PbPb collisions in spite of formidable combinatorial background (true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible



J/psi production in PbPb collisions: LHC relative to RHIC

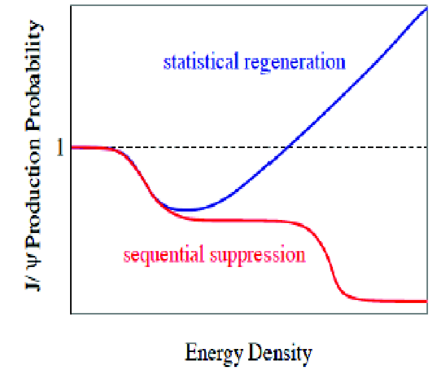
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{\rm ch}^{AA}/d\eta\, dp_T}{\langle N_{\rm coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{\rm ch}^{pp}/d\eta\, dp_T}$$



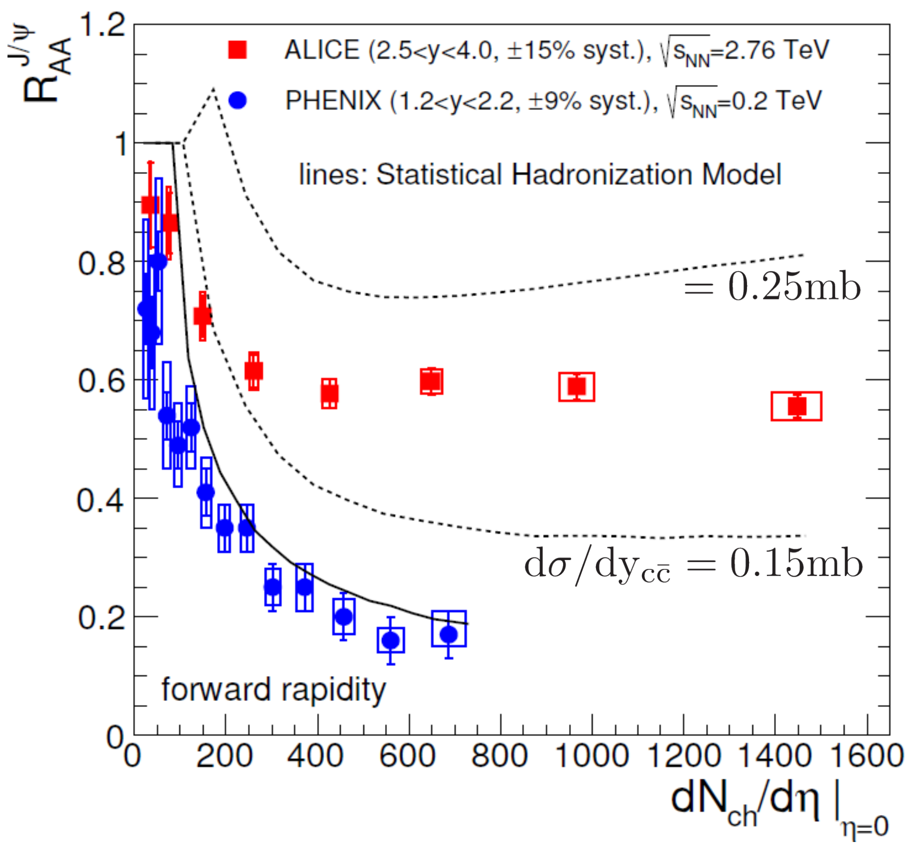


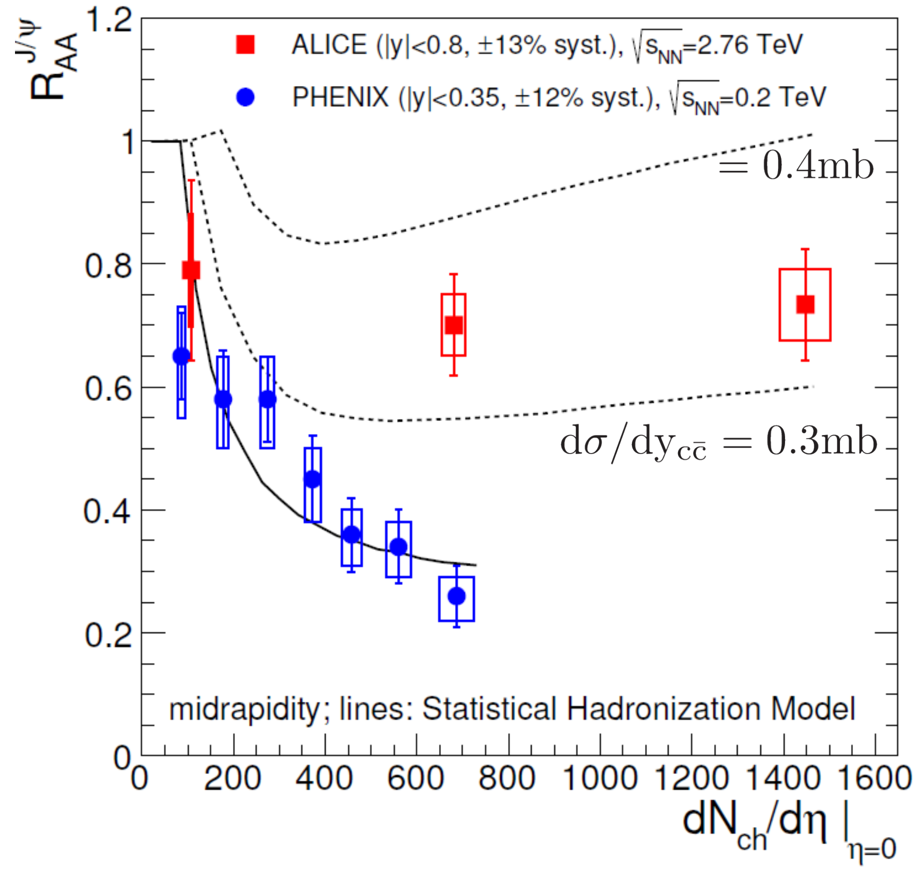
energy density -->

melting scenario not observed
rather: enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)



J/psi and statistical hadronization

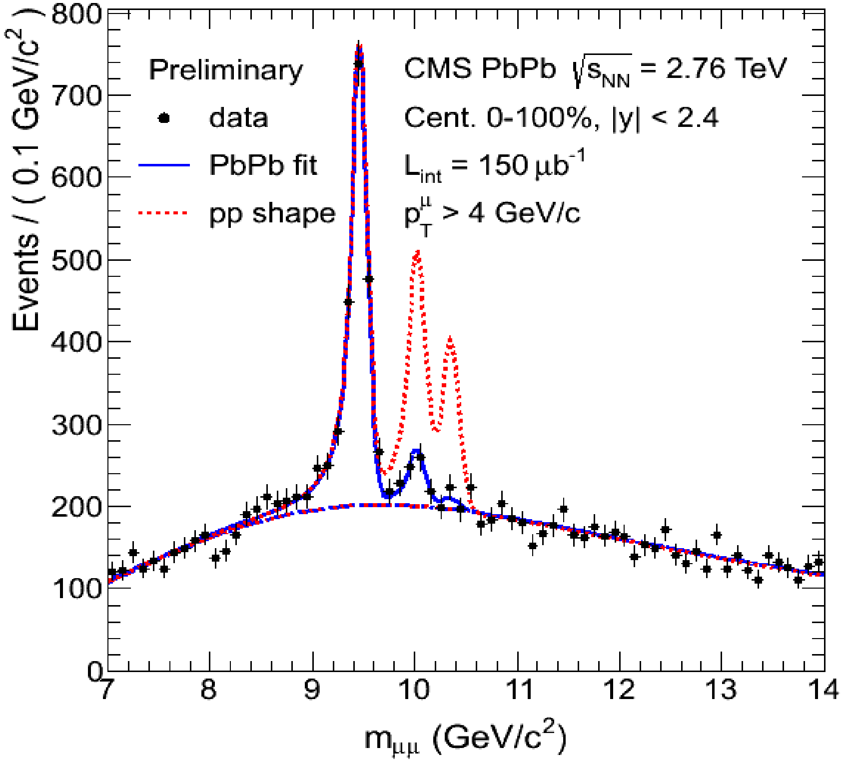


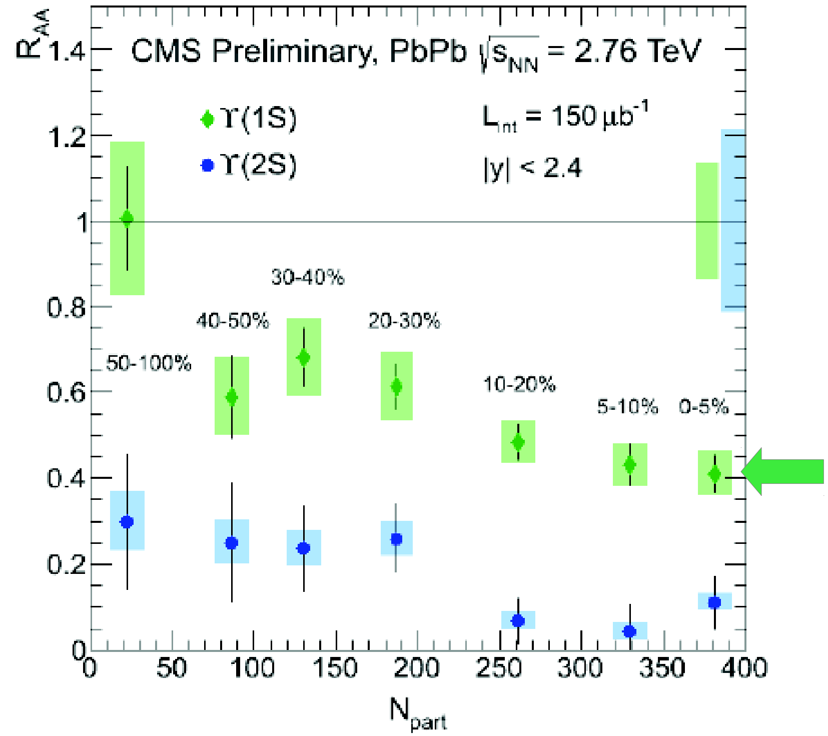


production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties

main uncertainties for models: open charm cross section, shadowing in Pb

First information on Upsilon states for PbPb at LHC





CMS-HIN-11-011

too strong for excited state suppression only (recently established by LHCb)

consistent with expectation that more loosely bound 2S and 3S states are more strongly suppressed

open question today: could also Upsilon form statistically at hadronization? Magnitude of R_{AA} ok for this